

Chapter 1

An Introduction to the Concept of Cooperating Objects and Sensor Networks

This chapter introduces concepts on cooperating objects and wireless sensor networks that will be used in the following chapters. It also introduces the Embedded WiSeNts Coordination Action. Finally, it presents an overview of the book and the relations between the following chapters.

1.1. Cooperating objects and wireless sensor networks

The evolution of embedded systems, together with the developments of technologies for integration and miniaturization, has led to the emergence of diverse devices, machines and physical objects of everyday use with embedded capabilities for computation, communication and interaction with the environment. These entities or objects range from millimeter-scale devices containing sensors, computing resources, bi-directional wireless communications and power supply to portable devices, home appliances, consumer electronic products or even machines and vehicles with on-board embedded controllers. The performance of all the above objects is limited by technology constraints and by the cost of performing particular functions and tasks. However, the cooperation of these objects may provide unprecedented capabilities and support for applications in many different fields. This cooperation requires the development of suitable methods and tools to support distributed interactions with the environment, adaptation to dynamic evolving working conditions, efficient use of resources, dependability and security constraints, amongst others.

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Today's technical systems are becoming more and more complex. While, so far, individual entities have frequently been sufficient for efficient control of individual parts of the system, the growing complexity of the system necessitates the cooperation of individual entities. This is particularly true for embedded systems. Embedded systems are themselves characterized by an intrinsic need to interact with the environment. This interaction can take place in the form of sensing as well as actuation. Because of system complexity, isolated entities can no longer perform this interaction efficiently and achieve the required control objectives. Hence, in the interaction with, exploration of and control of the environment, cooperation between individual entities becomes a necessity.

A fundamental notion in the above context is the concept of a *Cooperating Object* (CO). A CO can be defined as a collection of sensors, actuators, controllers or other COs that communicate with each other and are able to achieve, more or less autonomously, a common goal. The sensors retrieve information from the physical environment. The actuators modify the environment in response to appropriate commands. Thus, sensors and actuators form the hardware interfaces with the physical world. The controllers process the information gathered by sensors and issue the appropriate commands to the actuators, in order to achieve control objectives. The inclusion of other cooperating objects as part of a CO itself in a recursive manner indicates that these objects can combine their sensors, controllers and actuators in a hierarchical way and are therefore able to create arbitrarily complex structures.

Wireless Sensor Networks, or more generally *Wireless Sensor and Actuator Networks*, are typical examples of the above-mentioned cooperation. Such networks consist of objects that are individually capable of simple sensing, actuation, communication and computation, but the full capabilities of such networks are reached only by the cooperation of all these objects. These networks can, in turn, cooperate themselves with other individual, intelligent objects, other networks, other controllers, or even users via proper interfaces. While these "cooperating objects" represent a potentially disruptive technology, the concrete realization of this vision is still unclear.

A number of different system concepts have become apparent in the broader context of embedded systems over the past years. First, there is the classic concept of embedded systems as being mainly a control system for a physical process (machinery, automobiles, etc.). Second, more recently, the notion of pervasive and ubiquitous computing has evolved, where objects of everyday use can be endowed with some form of computational capacity, and perhaps with some simple sensing and communication facilities. Third, and most recently, the idea of "wireless sensor networks" has arisen, where entities that sense their environment are not operating individually, but collaborate together to achieve a well-defined purpose of supervision of a particular area, process, etc. We claim that these three types of actually quite diverse state of the art systems on one hand share some principal common features and, on the other hand, have some complementary aspects that make their combination very promising.

In particular, the important notions of control, heterogeneity, wireless communication, dynamic/ad hoc nature and cost are prevalent to various degrees in each of these concepts.

The main vision is the conception of a future-proof system that combines the strong points of all three system concepts at least in the following functional aspects:

- support the control of physical processes in a similar way that embedded systems are able to do today;
- have as good support for device heterogeneity and spontaneity of usage as pervasive and ubiquitous computing approaches have today;
- be as cost-efficient and versatile in terms of the use of wireless technology as wireless sensor networks are.

Figure 1.1 illustrates the above concepts.

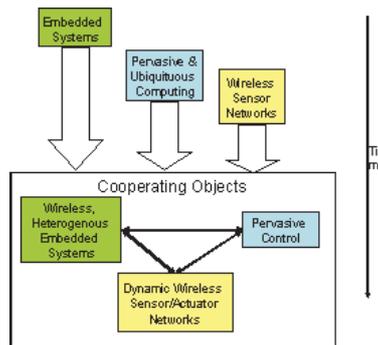


Figure 1.1. *Cooperating objects*

The commercial application of some concepts and technologies presented in this book is heavily dependent on the development of several supporting technologies. The first group of supporting technologies deals with miniaturization. It includes micro and nanotechnologies for new sensors and actuators and also the progress on micro and nano systems for computing and communications, including, for example, the “nets-on-chip” technology. The second group is the communication technologies themselves including new developments to support increasing mobility and bandwidth. The third group deals with power sources and includes not only the primary technologies to generate power but also the so-called energy harvesting technologies. The last group includes all aspects related to the intelligent management of cooperating objects interacting autonomously with the environment, and thus involving technologies such as networked control and networked robotics. All these technologies are not the subject of this book but they will influence the practical implementation of the presented concepts and techniques.

1.2. Embedded WiSeNts

This book is the result of the work developed in the Coordination Action (CA) entitled *Cooperating Embedded Systems for Exploration and Control featuring Wireless Sensor Networks – Embedded WiSeNts*, funded by the European Commission under the Information Society Technology (IST) priority within the 6th Framework Programme (FP6).

The project supports the establishment of a new research domain that integrates the broad context of embedded systems with ubiquitous computing and wireless sensor networks in support of COs. The key actions are concerned with integration of existing research in the field and related fields, supporting teaching and training in the area of COs and developing a technology roadmap to drive the vision forward.

Embedded WiSeNts is a joint effort between 12 partners from 10 different European countries: Technische Universität Berlin (coordinator, Germany), University of Cambridge (United Kingdom), University of Copenhagen (Denmark), Swedish Institute of Computer Science (Sweden), University of Twente (The Netherlands), Yeditepe University (Turkey), Consorzio Interuniversitario Nazionale per l'Informatica (Italy), University of Padua (Italy), Swiss Federal Institute of Technology Zurich (Switzerland), Asociación de Investigación y Cooperación Industrial de Andalucía (Spain), Institut National de Recherche en Informatique et en Automatique (France) and Universität Stuttgart (Germany).

These partners are among the top research institutions in wireless communication and distributed computing as well as in cooperating objects in general, and are at the forefront of ubiquitous communication and wireless sensor networks in particular. The project took place from September 1st 2004 to December 31st 2006.

The three main goals of this CA have been as follows.

1. Supporting the integration of existing research

This goal included the development of a survey of Platforms and Tools with a critical evaluation of Wireless Sensor Network platforms, operating systems, programming and simulation environments and testbeds.

2. Road mapping for technology adoption

This goal included:

- State of the art studies: a survey of the current state of the art and open research issues.
- Visions for innovative applications: exploring application areas that could potentially be realized in a 10-year horizon once CO-technology becomes widely available.

- Research roadmap: describing emerging trends and technological opportunities and proposing a research agenda. Distinguishing features of the roadmap are:
 - list of important gaps in the field and current trends, including an estimation of the time when each gap will be solved;
 - market analysis rating the importance of different application areas; suggestions for predominant work areas that should be tackled in the future;
 - organization of research describing needed interactions between main research groups;
 - potential roadblocks or major inhibitors that hinder the acceptance of CO technology in society.

3. Promoting excellence in teaching and training on systems of cooperating objects

This goal included the improvement of teaching material (Teachware) as well as the dissemination and development of a repository for teachers and students listing courses and teaching materials on COs.

An intended important result has been to increase the awareness of cooperating object technology within the academic community and, most importantly, within the industrial producer and user community. The resulting strategic impact will be that the options and the potential for the use of Embedded WiSeNts technologies will be available to selected decision makers in academia and industry.

The practical impact could be double on the manufacturers of such devices, providing them with required information on the type of devices that will be required in the future as well as incorporating their feedback on technical feasibility, enabling these manufacturers to lead the market in the production of the required technology.

The impact could also be on the adopters of such devices and the concept of the cooperating object system more generally, allowing them to form an understanding of the possibilities, market chances, product options, possible services surrounding this concept, etc., again contributing to and ensuring decisive competitiveness advantages. As a consequence, the introduction of cooperating objects in actual products will be hastened and the overall efficiency could be improved.

1.3. Overview of the book

The four following chapters of this book correspond to the studies carried out in the framework of the Embedded WiSeNts CA. The objectives of these studies are:

- an in-depth analysis of the current state of the art in Cooperating Embedded Systems and Wireless Sensor Networks;
- to identify open issues and trends in the field.

The book aims to provide a comprehensive and detailed overview of the scenarios, paradigms, functions and system architectures dealing with COs.

Chapter 2: Applications and application scenarios

Chapter 2 provides an initial overview of CO applications and application scenarios. The main objective is to identify relevant state of the art, projects and activities in the CO domain. Some application scenarios enable us to better understand the area of CO in the broad sense of the term from two different perspectives: socio-economic and application-type aspects have been identified and developed. First, general application characteristics for all domains are identified. Then, a survey of state of the art CO projects is given.

In the next section of the chapter, CO applications have been classified in sectors which have a social and economic impact on society. The classification is then used as a basis for the analysis of common characteristics in the field of action. Some application scenarios from different domains have been chosen and they are given along with their typical parameters, requirements, roles, traffic, threads, legal/economic issues that best characterize the research performed in the field of cooperating objects in the broad sense of the term. Considering the current trends, the following areas which can benefit from cooperating objects are defined:

- control and automation
- home and office
- logistics
- transportation
- environmental monitoring for emergency services
- healthcare
- security and surveillance
- tourism
- education and training

In this chapter you can also find a summary of the outcome of the study which will later be used as a measurement for the importance of the application domain and will act as a means of weighting conflicting requirements.

Chapter 3: Paradigms for algorithms and interactions

This chapter provides an up-to-date overview of the fundamental design paradigms, algorithms and interaction patterns that enable the realization of systems based on COs. In order to cope with the large heterogeneity of CO systems, the literature has been divided into four thematic areas, namely:

- Wireless Sensor Networks for Environmental Monitoring characterized by a large number of stationary sensor nodes, disseminated in a wide area and one (or a few) sink nodes, designated to collect information from the sensors and act accordingly. Depending on the user scenario, nodes can be either accurately placed in the

area according to a pre-planned topology or randomly scattered over the area, except for a limited number of nodes that are placed in specific positions, for instance to guarantee connectivity or to act as beacons for the other nodes. Finally, a random topology is obtained when nodes are scattered in the area without any plan. Sensor nodes are often inaccessible, battery powered, or prone to failure due to energy depletion or crashes. Furthermore, network topology can vary over time due to the power on/off cycles that nodes go through to save energy. Generally, traffic in Wireless Sensor Networks for Environmental Monitoring flows mostly from sensors to one or more sinks and vice versa, and data may show a strong spatial correlation. Since nodes are usually battery powered and not (easily) rechargeable, power consumption is a primary issue.

- **Wireless Sensor Networks with Mobile Nodes** ranging from a network with only mobile nodes to a network with a trade-off between static and mobile nodes. The use of mobile nodes in sensor networks increases the capabilities of the network and allows dynamic adaptation to the environmental changes. Some applications of mobile nodes could be: collecting and storing sensor data in sensor networks reducing the power consumption due to multi-hop data forwarding, sensor calibration using mobile nodes with different and possibly more accurate sensors, reprogramming nodes “by air” for a particular application and network repairing when the static nodes are failing to sense and/or to communicate. The mobile nodes can collect the data from the sensors and send it to a central station by using a long-range radio technology, thus acting as mobile sinks. Usually, the traffic between static and mobile nodes is low, whereas the traffic among mobile nodes and the central station is high. The mobile nodes can also process the information gathered from the static nodes in order to reduce the data traffic. Power consumption is still an issue but mobile nodes can reduce the power consumed in multi-hop data forwarding. Furthermore, it is possible to have energy stations where mobile nodes can recharge their batteries.

- **Autonomous Robotic Teams** that make it possible to build more robust and reliable systems by combining redundant components. The topology is often pre-planned because the motion of the robots is always to some extent controlled and predictable, and the data traffic among the robots is usually higher (images, telemetry, etc.) than the traffic among the nodes of a WSN. Moreover, traffic patterns are more similar to the classic all-to-all paradigm considered in ad hoc networks. Furthermore, the cooperation and/or coordination of the robots require very heavy data processing. Nevertheless, Autonomous Robotic Teams usually do not have severe energy constraints, since robots can autonomously recharge their batteries when a low level of energy is detected. Also, mixed solutions including solar panels are possible. In opposition to the other distributed systems here considered, these teams can require real-time features, depending on the particular application.

- **Inter-vehicular Networks**, which is a promising approach to address critical road safety and efficiency, for example, coordinated collision avoidance systems. These networks exhibit characteristics that are specific to scenarios of high node mobility and, despite the constraints on the movement of vehicles, the network will tend to

experience very rapid changes in topology. Some applications require communication with destinations that are groups of vehicle and thus the traffic pattern is predominantly multicast, while the data rate is generally rather high (car-to-car voice/video connections, web surfing, etc.). Unlike typical WSN deployment scenarios, vehicles can be instrumented with powerful sensors and radio to achieve long transmission ranges and high quality sensor data, since low-power consumption and small physical size are not an issue in this context.

As such, the above thematic areas differ in characteristics and requirements and, we believe, are representative of a number of possible application scenarios.

For each thematic area, the chapter provides a rather comprehensive survey of the most interesting algorithms proposed in the literature for the following aspects:

- MAC, routing, localization,
- data aggregation and data fusion,
- time synchronization,
- navigation,
- object coordination and cooperation.

The algorithms and paradigms are thus classified according to the requirements that have been identified in Chapter 2. In this way, the study makes it possible to clearly identify common features and differences among the different design paradigms adopted in each specific system, thus revealing the most promising research trends and research gaps that should be covered in the near future.

Therefore, the study collects and compares the different approaches and solutions proposed in the literature for the realization of the basic functionalities of CO-system, and a summary of the research gaps and the promising approaches regarding the algorithms and paradigms for the realization of CO-systems.

Chapter 4: Vertical system functions

This chapter complements the previous three chapters in identifying the relevant state of the art in the context of distributed COs and WSNs.

The set of characteristics exhibited in CO applications are more diverse than those found in applications of traditional wireless and wired networks. The set of requirements includes among other things the location and context of COs, security, privacy and trust, system scalability and reliability, to mention a few.

Critical factors impact on the architectural and protocol design of such applications. Organizing software and hardware components of COs into a framework that

can cope with the inherent complexity of the overall system will be an important exercise for application developers.

The current operating systems proposed for WSNs and COs cannot offer all the required functionality to these applications. The main goal of this chapter is to discuss the roles and effects of vertical system functions (VFs), which are defined in this chapter as the functionalities that address the needs of applications in specific domains and in some cases a VF also offers minimal essential functionality that is missing from available real-time operating systems.

The chapter revisits and reviews the most relevant application requirements and discusses the most suitable VFs to address these needs. It is organized as follows:

- Definition of vertical system functions in the context of cooperating objects.
- Discussion of the characteristics and requirements of the CO application studied in Chapter 2.
- Different types of VFs to address the application needs (section 4.4). The VFs discussed are:
 - Context and location management.
 - Data consistency.
 - Communication functionality.
 - Security, privacy and trust.
 - Distributed storage and data search.
 - Data aggregation.
 - Resource management.
 - Time synchronization.

The chapter concludes with a summary of trends and open issues identified. Briefly, the most urgent issues that deserve the attention of the research community are the distributed accurate location of COs and system support for node mobility and sensor heterogeneity. The software framework requires consolidation using standardized APIs and high-level descriptive language. In practical terms, there is a need for deployment and configuration of sensors in real application scenarios.

Chapter 5: System architectures and programming models

Key to the successful and widespread deployment of cooperating objects and sensor network technologies is the provision of appropriate programming abstractions and the establishment of efficient system architectures able to deal with the complexity of such systems. This chapter provides a survey about the current state of the art of programming models and system architecture for COs and motivates their importance for a successful development of these technologies. The second section of this chapter

provides a brief introduction to the topics and motivates the need to design suitable programming abstractions for COs.

In the third section, the most relevant existing programming abstractions are surveyed and classified. A programming model is considered as “a set of abstractions and paradigms designed to support the use of computing, communication and sensing resources in an application” and to a system architecture as “the structure and organization of a computing system, as a set of functional modules and their interactions”. The main reason for the development of these abstractions is to allow a programmer to design applications in terms of global goals and to specify interactions between high level entities (such as agents or roles), instead of explicitly managing the cooperation between individual sensors, devices or services. For example, the database abstraction makes it possible to consider a whole sensor network as a logical database, and performs network-wide queries over the set of sensors. The various paradigms are surveyed and a set of criteria making it possible to easily review their strengths and weaknesses are presented.

The next section presents the existing system architectures for COs at two different levels: first, system architectures of individual nodes, which includes the structure of the operating system running at node level and its facilities; second, system architectures supporting the cooperation of different nodes, such as communication models.

Finally, the chapter points out some of the limitations of current approaches, and proposes some research perspectives. In particular, programming paradigms should provide more support to facilitate programming and heterogeneity, as well as scalability issues. Regarding system architectures, real-time aspects, which currently are not well addressed, will become increasingly important for COs. Dynamic maintenance (such as code deployment and runtime update support) is another important issue to address in future systems. Finally, effort is required to better integrate the various paradigms and systems into a unified framework.

Although the four chapters are focused on different aspects concerning COs, they are strictly inter-related. Figure 1.2 points out some of these relations.

Chapter 6: Cooperating objects roadmap and conclusions

The last chapter of this book provides a brief summary of the roadmap developed as part of the Embedded WiSeNts work with input from associated industrial and academic partners. A full version of this roadmap can be obtained as a separate book from Logos Verlag, Berlin and is also available online from the project website (<http://www.embedded-wisents.org>).

The roadmap, being the final result of the project, takes into account the information contained in the previous chapters to define the research trends and gaps, therefore identifying the potential research directions that the CO community will take in the

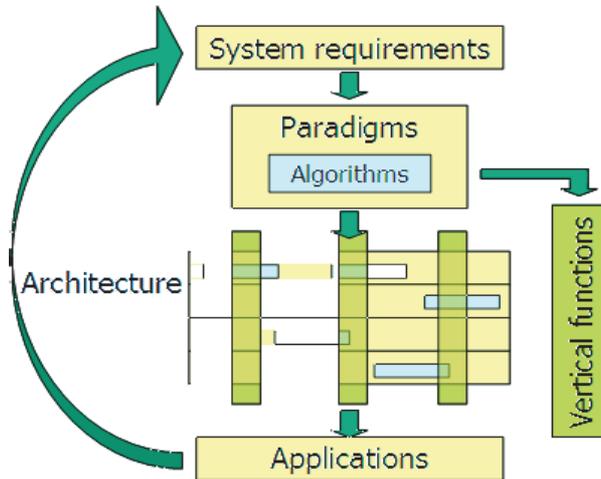


Figure 1.2. Relations between chapters

next 10 to 15 years. The executive summary provided as part of this chapter concludes with a series of recommendations and specific actions that can be taken into account by the research community, industry and end-users.